TOWARDS SUSTAINABLE EXTRACTION OF OIL FROM APRICOT KERNELS

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Abstract: Deep eutectic solvents (DES) are gaining attention as green alternatives to conventional volatile organic solvents for the extraction of natural products. Their ease of preparation from inexpensive, biodegradable components, along with low toxicity and tunable physicochemical properties, makes them promising candidates for designing eco-efficient extraction processes. In this work, four DES systems based on choline chloride (ChCl) as hydrogen bond acceptor and different hydrogen bond donors glycerol, lactic acid, acetic acid, and glucose were synthesized and evaluated as co-solvents with *n*-hexane for the ultrasonic-assisted extraction of oil from apricot kernels. The DESs were characterized in terms of pH, density (δ), viscosity (μ), and electrical conductivity (σ) to better understand how their physical properties influence extraction performance. Oil extraction experiments demonstrated that the DES composition and its physical properties have a marked impact on extraction efficiency. Under optimized ultrasonic conditions, the use of ChCl:AA (1:2) as a co-solvent with *n*-hexane yielded the highest oil recovery of 26.62%, surpassing pure *n*-hexane, which afforded only 24.10% under the same conditions. In contrast, ChCl:GLY (1:2), ChCl:LA (1:2), and ChCl:GLU (2:1) resulted in lower oil yields of 18.95%, 22.23%, and 13.26%, respectively. The superior performance of ChCl:AA is attributed to its combination of relatively low viscosity, and high conductivity, which collectively promote enhanced mass transfer, more efficient cell disruption, and improved solubilization of lipophilic components when assisted by ultrasonic cavitation. Overall, this study highlights the importance of tailoring the physicochemical properties of DES to maximize performance and demonstrates the potential of DES *n*-hexane systems as green, efficient, and scalable alternatives to conventional solvent based processes for the valorization of apricot kernel oil and other plant derived lipids.
Keywords: deep eutectic solvents, green extraction, apricot kernel oil, choline chloride

1. INTRODUCTION

Natural products and bio-derived compounds continue to attract widespread scientific interest due to their broad pharmacological, nutraceutical, and industrial relevance. These molecules, produced by plants, microorganisms, and other biological systems, often display potent biological activities that support their extensive use in drug development, functional foods, cosmetics, and other commercial sectors (Atanasov, 2021). The chemical diversity of natural metabolites is shaped by factors such as species, environmental conditions, and geographic origin, resulting in a wide spectrum of structures and bioactivities. In recent years, attention has increasingly shifted toward underutilized plant materials including agricultural by-products such as husks, shells, kernels, peels, and seed residues as promising, cost effective sources of bioactive constituents (Saini, 2025; Donno, 2020; Gomes-Araujo, 2021). Numerous studies have shown that these by-products contain high levels of phenolics, lipids, vitamins, and other metabolites with antioxidant, antimicrobial, and health promoting properties (Nandasiri, 2021; Bangar, 2022).
Among these components, seed oils are of particular significance due to their rich profiles of unsaturated fatty acids, phytosterols, and other valuable lipophilic compounds. Such constituents contribute to improved cardiovascular health, anti-inflammatory effects, and oxidative stability, making seed oils attractive for food, pharmaceutical, and cosmetic applications (Poudyal, 2013). As a result, the development of efficient and sustainable oil extraction technologies remains a priority. Traditional extraction approaches including mechanical pressing, solvent extraction, and assisted techniques such as ultrasound or microwave irradiation are well established, yet many still rely on volatile organic solvents (VOCs) derived from petrochemical sources, which raise environmental and safety concerns (Chibuye, 2023).
In response to these limitations, green extraction strategies have gained momentum. Deep eutectic solvents (DESs), in particular, have emerged as a novel class of environmentally benign solvents formed from inexpensive and biodegradable hydrogen bond donors and acceptors (Yu, 2021). Due to their tunable physicochemical properties, low toxicity, and ease of preparation, DESs have been increasingly explored for the extraction of phenolics, pigments, essential oils, and other natural compounds from botanical materials (Liu, 2018; Vanda, 2018). Despite their growing application, the use of DESs for extracting lipophilic fractions such as seed oils remains relatively underexplored, with only a limited number of studies addressing this potential (Hayyan, 2022; Al-Mari, 2024).

Therefore, the present study investigates the application of deep eutectic solvents as alternative media for the extraction of oils from apricot kernels. By tailoring solvent composition and optimizing extraction parameters, this work aims to demonstrate the feasibility of DES assisted oil extraction and highlight the advantages of these solvents in terms of efficiency, selectivity, and sustainability.

2. MATERIALS AND METHODS

Chemicals and materials

Apricot fruits were sourced from a local fruit processing facility in North Macedonia. The collected seeds were dried in an oven (Electrothermal, Germany) at 60 °C for 24 h, followed by grinding and sieving (Controls, Germany) to obtain particle sizes of 4 mm, 2 mm, 1 mm, and 0.5 mm. The fraction with a particle size of 2 mm was kept at –20 °C prior to extraction. All chemicals including *n*-hexane, choline chloride, glucose, acetic acid, glycerol, and lactic acid were obtained from Sigma-Aldrich (Sweden) and used as received without any additional purification.

Conventional extraction method

Maceration was carried out with *n*-hexane at a ratio of 1:10 (w/v), at 60 °C for 1 h. After extraction, the mixture was allowed to cool to room temperature and subsequently filtered. The solvent in each extract was removed using a rotary vacuum evaporator (IKA, Germany) at 50 °C, and the resulting oil was stored in amber glass containers at –20 °C.

Preparation of Deep Eutectic Solvents (DESs)

Choline chloride (ChCl) was chosen as the hydrogen bond acceptor (HBA) for all DES formulations. Glycerol (GLY), lactic acid (LA), acetic acid (AA) and glucose (GLU) served as hydrogen bond donors (HBDs). The DESs were prepared by combining the HBA with each HBD at predetermined molar ratios, followed by heating the mixtures to 50 °C and stirring at 500 rpm for 30 min until homogeneous, viscous liquids were formed. The synthesized DESs were transferred into airtight glass bottles and stored until required for extraction experiments.

Physical properties of DESs

The pH of each synthesized DES was assessed using a calibrated digital pH meter (Mettler Toledo, Switzerland). Density measurements were carried out with a 25 mL glass pycnometer following a standard gravimetric procedure. The density (δ) was calculated using the equation:

$$??=\frac{m_1-m_0}{V}$$

- **m_1** = mass of the pycnometer filled with the solvent (g)
- **m_0** = mass of the empty pycnometer (g)
- **V** = pycnometer volume (cm^3)

Conductivity was determined using a digital conductivity meter (Thermo Fisher Scientific, USA). Dynamic viscosity was measured using a rotational viscometer (Brookfield, USA), with all measurements performed at room temperature under continuous stirring. Prior to analysis, the DES system ChCl:GLU was preheated in a water bath at 50 °C to ensure complete homogenization.

Extraction using DESs

Ultrasound-assisted extractions were carried out at 60 °C for 60 min using an ultrasonic device operating at 50 Hz, while maintaining a constant seed : *n*-hexane : DES ratio of 1:10:1 (w/v/w). Following the extraction period, the mixtures were allowed to cool to ambient temperature and were subsequently filtered to remove solid residues. The resulting filtrates were concentrated with a rotary vacuum evaporator (IKA, Germany) set to 50 °C. The recovered oils were then transferred into amber glass vials and stored at –20 °C until further analysis.

3. RESULTS

Physical properties of the synthesized DESs

The measured physical characteristics of the synthesized DES systems are presented in Table 1. The pH values showed substantial variation depending on the hydrogen bond donor (HBD) used. DESs composed with organic acids (ChCl:LA and ChCl:AA) exhibited strongly acidic pH values of 2.08 and 1.69, respectively, reflecting the influence of lactic and acetic acid. In contrast, systems formulated with polyols or sugars demonstrated higher pH levels, with ChCl:GLY showing moderately acidic behavior (pH 5.30) and ChCl:GLU being the most neutral (pH 6.80).

All DESs displayed densities within the typical range for choline chloride–based systems (1.16–1.30 g/cm^3). The highest density was observed for ChCl:GLU (1.30 g/cm^3), likely due to the high molecular weight and strong hydrogen bonding capacity of glucose, while ChCl:AA exhibited the lowest density (1.16 g/cm^3).

Viscosity varied dramatically across the different formulations. The ChCl:GLU system showed an exceptionally high viscosity (8000 mPa·s), characteristic of sugar-based DESs with extensive intermolecular interactions. Moderate viscosities were recorded for ChCl:GLY (370 mPa·s) and ChCl:LA (500 mPa·s), whereas ChCl:AA exhibited the lowest viscosity (55 mPa·s), indicating weaker hydrogen bond networks compared to the other systems.

Table1. Physical properties of the synthesized DESs

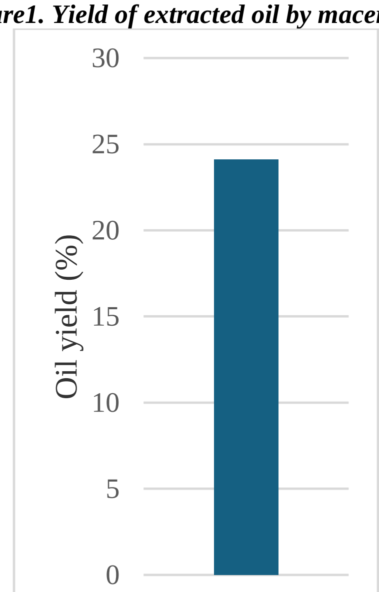
Deep eutectic solvent	pH	δ (g/cm^3)	μ (mPa·s)	σ (mS)
Choline chloride: glycerol=1:2	5.30	1.22	370	3.41
Choline chloride: lactic acid=1:2	2.08	1.22	500	1.96
Choline chloride: acetic acid=1:2	1.69	1.16	55	4.70
Choline chloride: glucose=2:1	6.80	1.30	8000	0.003

Electrical conductivity followed an inverse trend relative to viscosity. The most fluid DES, ChCl:AA, displayed the highest conductivity (4.70 mS), suggesting efficient ion mobility. ChCl:GLY and ChCl:LA showed intermediate conductivities (3.41 and 1.96 mS, respectively), whereas the highly viscous ChCl:GLU had extremely low conductivity (0.003 mS), consistent with its restricted ion transport.
Overall, the results confirm that the physicochemical behavior of DESs is strongly dependent on the nature of the HBD. Systems based on acids tend to be more fluid and conductive, while sugar based DESs exhibit higher viscosity and lower ionic mobility. These differences are expected to affect mass transfer efficiency and extraction performance in subsequent experiments.

Conventional extraction method

The maceration process, performed with *n*-hexane at a 1:10 ratio (w/v) and maintained at 60 °C for 1 h, yielded 24.10% oil, indicating a relatively high extraction efficiency under these conventional conditions.

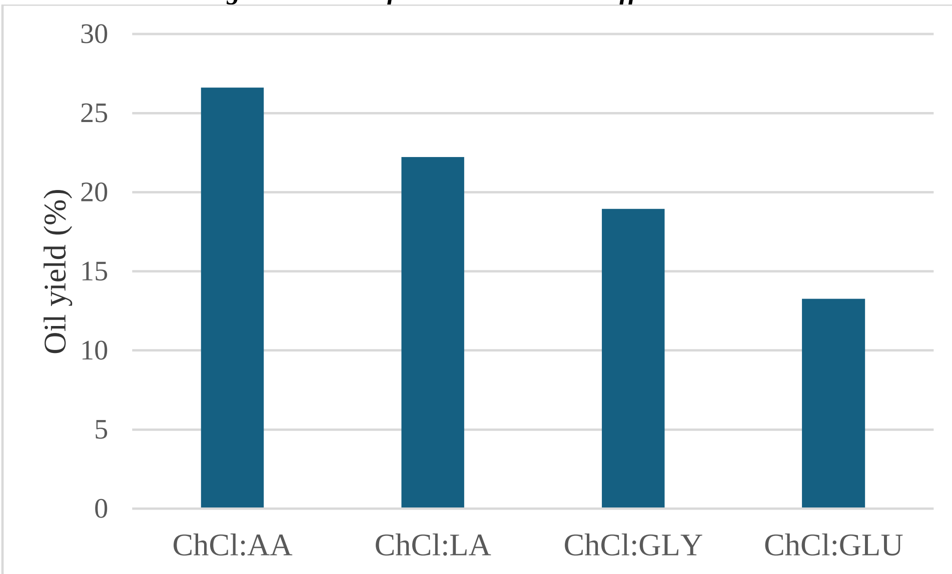
Figure1. Yield of extracted oil by maceration



Extraction using DESs

Ultrasound-assisted extraction performed at 60 °C for 60 min using a seed : *n*-hexane : DES ratio of 1:10:1 (w/v/w) enabled a direct comparison of the different DES systems. The extraction efficiency varied notably depending on the HBD component. The ChCl:GLU formulation produced an oil yield of 13.26%, while ChCl:GLY resulted in 18.95%. Higher yields were achieved with the acid based DESs, with ChCl:LA providing 22.23% and ChCl:AA yielding the highest value of 26.62%.

Figure 2. Yield of extracted oil with different DESs



Overall, these results indicate that the nature of the hydrogen-bond donor significantly influences extraction performance, with the acid based DESs demonstrating superior efficiency.

4. DISCUSSIONS

Our earlier review of apricot kernel oil extraction techniques (Amiti, 2024) highlighted that both conventional approaches (cold pressing, Soxhlet extraction) and more advanced methods, such as supercritical fluid extraction, have been widely examined in the literature. Among these, Soxhlet extraction with non-polar solvents including *n*-hexane and petroleum ether remains the dominant technique due to its efficiency and strong solvent lipid affinity. To the best of our knowledge, the use of DESs for extracting oil from apricot kernels has not been previously reported, despite increasing interest in these solvents as environmentally friendly alternatives to conventional extraction media. In this study, we synthesized a set of choline chloride based DESs using glycerol, glucose, lactic acid, and acetic acid as hydrogen bond donors (HBDs), enabling a comparative assessment of how variations in solvent composition and physicochemical properties influence extraction efficiency.

The extraction results demonstrated that the chemical nature of the DES components played a decisive role in oil recovery. Among the tested formulations, the acid based DESs (ChCl:LA and ChCl:AA) exhibited the highest extraction yields, whereas DESs formulated with glycerol and glucose resulted in lower recoveries. This trend reflects the combined influence of polarity, viscosity, and hydrogen bonding behavior on mass transfer processes. Acid based DESs generally possess lower viscosities and higher conductivities, which support improved molecular mobility and solvent penetration into the kernel matrix. Their moderate polarity may also facilitate more efficient solubilization of lipophilic components compared to highly viscous or strongly hydrogen bonded systems such as ChCl:GLU, which showed the poorest extraction performance. Maceration with *n*-hexane produced 24.10% oil, while the ChCl:AA DES achieved the highest yield at 26.62%, outperforming the conventional method. This result indicates that acid based DESs, particularly ChCl:AA, can enhance oil recovery from apricot kernels under the tested conditions.

These results are consistent with previous studies highlighting the capacity of certain DES formulations to enhance oil extraction efficiency. For example (Zare Nezhad, 2021) reported that the ChCl:EG (1:2) system improved oil recovery from halophytic safflower and salicornia species. In flaxseed extraction, the same DES used alongside *n*-hexane produced slightly higher yields than *n*-hexane alone and allowed the process to operate at lower optimal temperatures (Hayyan, 2022). Comparable findings were observed for rubber seed oil, where ChCl:GLY (1:2) employed as a co-solvent increased the extraction yield to 30.7%, outperforming pure diethyl ether, which yielded 27.0% (Al-Mari, 2024). These studies collectively demonstrate that appropriately selected DESs can positively influence mass transfer and solvent performance during oil extraction.

5. CONCLUSIONS

This study demonstrates the potential of choline chloride–based DESs as effective green co-solvents for apricot kernel oil extraction. Among the synthesized systems, the ChCl:AA DES provided the highest oil yield (26.62%), outperforming conventional maceration with *n*-hexane (24.10%) and confirming the strong influence of DES composition on extraction efficiency. The results also align with previous reports showing that carefully selected DESs can enhance oil recovery from various plant materials. Overall, the findings highlight DESs as promising alternatives to traditional organic solvents for developing more sustainable and efficient extraction processes.

Table 2. Abbreviations

DES	Deep eutectic solvent
ChCl:EG	Choline chloride: ethylene glycol
ChCl: GLU	Choline chloride: glucose
ChCl:GLY	Choline chloride: glycerol
ChCl:AA	Choline chloride: acetic acid
ChCl:LA	Choline chloride: lactic acid
VOC	Volatile organic compounds
HBD	Hydrogen bond donor
HBA	Hydrogen bond acceptor

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