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REVIEW PAPER

GREEN EXTRACTION OF BIOACTIVE COMPONENTS FROM *Phoenix dactylifera* (L.) SEEDS USING NADES: APPLICATIONS IN FUNCTIONAL FOOD INGREDIENTS

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Abstract

Date seeds, often considered agro-industrial waste, are a rich source of bioactive compounds such as polysaccharides, mono-oligosaccharides, phytosterols, carotenoids, and polyphenols, all possessing significant functional properties. This review explores the extraction of these compounds using Natural Deep Eutectic Solvents (NADES), a green, biodegradable, and cost-effective alternative to conventional solvents. The extraction efficiency is enhanced when NADES is combined with advanced techniques such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and heating-stirring-assisted extraction (HSAE). Optimal NADES formulations include choline chloride and lactic acid with UAE for polyphenols catechins, choline chloride and ethylene glycol with UAE for polysaccharides, menthol and eucalyptol with HSAE for phytosterols. Additionally, specific NADES combinations facilitate the extraction of carotenoids using Octanoic acid and L-proline with HSAE under controlled conditions. Extracts obtained using choline chloride and ethylene glycol with MAE exhibit promising applications in functional food systems, including food preservation. Notably, polyphenol-rich extracts have been shown to extend the shelf life of *Oreochromis niloticus* fillets stored at 4°C for up to 10 days. These findings underscore the potential of NADES-extracted date seed components as sustainable food ingredients, aligning with green chemistry principles and contemporary food technology trends.

Keywords: NADES, date seeds, modern-assisted extraction, functional food ingredients, green chemistry

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Introduction

Natural deep eutectic solvents (NADES) offer several advantages, including their composition from "natural" components, alignment with green technology principles, and potential applications in the food and beverage industry (Vanda et al., 2018). These solvents have been shown to efficiently produce plant metabolite extracts with higher yields compared to conventional organic solvents. Moreover, NADES exhibit lower toxicity, reduced environmental impact, and cost-effectiveness (Guo *et al*., 2019). Additionally, their high stabilization capacity and excellent solubility further establish NADES as promising alternatives to conventional organic solvents (Chemat *et al*., 2019).
According to Food and Agriculture Organization (FAO) data, global date production in 2022 reached around 9.75 million tons. Date seeds usually contribute around 10-15% of the total weight of dates. Thus, the date seed waste produced globally is estimated to reach between 975,000 and 1,462,500 tons annually (Faleiro and Krishna Kumar, 2023). Date seeds, a by-product of date palm (*Phoenix dactylifera* L.) processing, are often discarded despite their richness in bioactive compounds such as catechins and chlorogenic acid (Airouyuwa *et al*., 2023b). These compounds exhibit pharmacological properties, including anti-hyperlipidemic (Hasan and Mohieldein, 2016), anti-hyperglycemic (Abiola *et al*. 2017; Hasan and Mohieldein, 2016), and anti-inflammatory effects (Bouhlali *et al*., 2020; Saryono *et al*., 2020). Furthermore, enzymatic inhibition activities, such as lipase (77.14%), alpha-amylase (70.14%), and alpha-glucosidase (60.38%), highlight their potential for functional food applications (Hinkaew *et al*., 2021). Generally, the bioactivity of bioactive components in date seeds is higher than in the fruit (Alsuhaymi *et al*., 2023). Notably, the bioactivity of these components in date seeds often surpasses that found in the fruit itself, making them a valuable resource for developing sustainable food ingredients.

Historically, date seeds have been utilized in limited applications, such as animal feed or as additives in coffee substitutes. However, recent studies have demonstrated broader uses in food systems, including their incorporation into butter for oxidative stability, enrichment of biscuits with dietary fiber, and development of caffeine-free coffee powder (Venkatachalam and Sengottian, 2016). Additionally, date seed powder has been utilized as a prebiotic and natural stabilizer in yogurt (El-Kholy, 2018), while its extracts have shown promise as stabilizing agents in nanoemulsion-based functional foods and preservatives for *Oreochromis niloticus* fish fillets.

The isolation of bioactive compounds is essential for optimizing their functional potential. Conventional extraction methods, such as maceration, are limited by high solvent usage, extended processing times, and low yields. In contrast, modern techniques like Ultrasonic-Assisted Extraction (UAE) and microwave-assisted extraction (MAE), especially when combined with Natural Deep Eutectic Solvents (NADES), offer significant advantages. NADES, composed of hydrogen bond donors and acceptors, provides a green, biodegradable, and cost-effective alternative for extracting thermolabile phytochemicals (Benkerou *et al.* 2018; Liang *et al.* 2020; Mostafa *et al.* 2022).

This review explores the applications of date seed extracts as food ingredients, focusing on the efficiency and sustainability of NADES-based extraction methods. By aligning with the principles of green chemistry and the Sustainable Development Goals (SDGs), this study highlights the role of date seeds in advancing contemporary food technology (Liang *et al.* 2020; United Nations 2024).While previous reviews have explored the nutritional and pharmacological properties of date seeds, as well as general extraction techniques, there remains a lack of comprehensive analysis on applying NADES for optimizing bioactive compound extraction. This review addresses this gap by evaluating the efficiency and sustainability of NADES-based methods, contributing to the development of green extraction techniques for food ingredient applications.

Materials and methods

The comprehensive review in this manuscript is compiled based on a literature study obtained from a database portal referring to 80 papers in Scopus, Science Direct, PubMed, Research Gate, and Google Scholar (a total of 80 papers). Furthermore, duplicated manuscripts, those that do not match the keywords, and only have abstracts were removed and 59 manuscripts last 10 years were selected related to date seed, NADES, extraction, bioactive components, food ingredients, non-conventional methods, and green chemistry until December 2024.

Results and discussion

Extraction techniques using Natural Deep Eutectic Solvents (NADES)

Natural Deep Eutectic Solvents (NADES) are eutectic mixtures composed of hydrophilic hydrogen bond acceptors (HBAs), such as choline chloride, betaine, and acetylcholine, or hydrophobic HBAs, such as menthol, thymol, and organic acids, combined with primary metabolite hydrogen bond donors (HBDs), such as sugars (glucose, fructose, sucrose, xylose), organic acids (lactic acid, ascorbic acid), and amino acids (lysine, glycine) (Dai et al., 2013). NADES offer numerous advantages, including high biodegradability, low toxicity, excellent solute stabilization, environmental sustainability, and cost-effective synthesis (Choi *et al.* 2011; Espino *et al.* 2016).

NADES have garnered attention for their effectiveness in extracting bioactive compounds when combined with advanced techniques, such as ultrasonic-assisted extraction, microwave-assisted extraction, and pressurized liquid extraction. Ultrasonic methods using NADES have been shown to efficiently extract phytochemicals, including polyphenols (Liang *et al*., 2020), polysaccharides, sugars (Zhang and Wang, 2017), phenolic acids, flavonoids (Alrugaibah *et al*., 2021), and carotenoids (Koutsoukos *et al*., 2019). Additionally, these methods have been effectively applied to extract biomolecules from plants, such as phenolic compounds (Đorđević *et al*., 2021), flavonoids, anthocyanins (Dai *et al*., 2016), polysaccharides (Gao *et al*., 2020), and proteins (Hernández-Corroto *et al*., 2020).

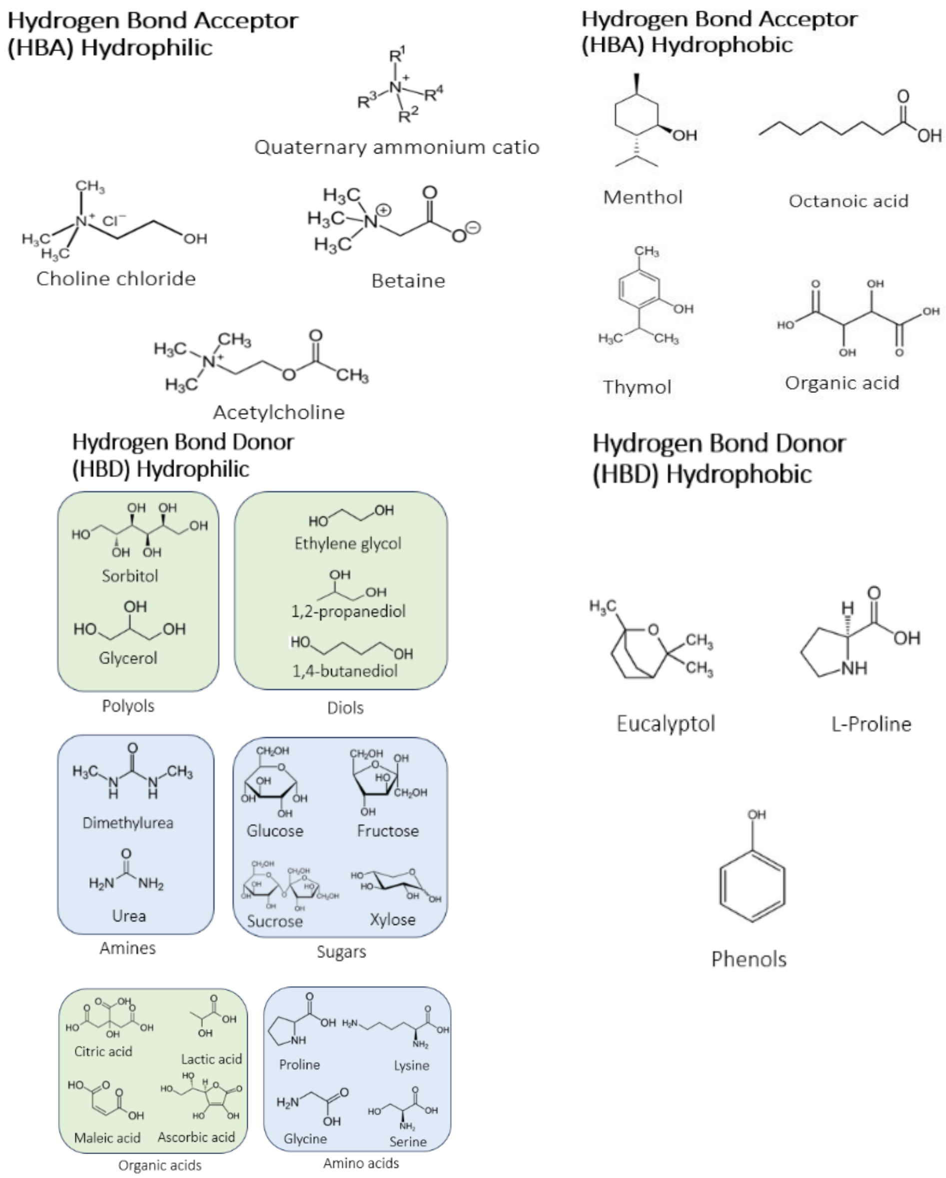

Figure 1. Structure of hydrophilic and hydrophobic NADES.

Choline chloride (ChCl) was selected as the hydrogen bond acceptor (HBA) for the synthesis of a natural deep eutectic solvent (NADES) (Figure 1) due to its hydrophilic nature. ChCl is a widely available quaternary ammonium salt, commonly utilized as an HBA in combination with various hydrogen bond donors (HBDs) for NADES synthesis across diverse applications, including extraction processes (Gao *et al*., 2020). Furthermore, ChCl is affirmed by the U.S. Food and

Drug Administration (FDA) and is approved for use as a food additive at the industrial scale (Huang *et al*., 2019).

NADES composed of ChCl and HBDs are classified as type III eutectic systems, which are simple to formulate, exhibit low reactivity with water, and are often biodegradable and cost-effective (Smith *et al*., 2014). In addition to ChCl, betaine-based NADES are also commonly utilized. However, the preparation of NADES using betaine is considered more challenging compared to ChCl (Huang *et al*., 2019; Ahmad *et al*., 2021).

For instance, Choline chloride and lactic acid represents a hydrophilic NADES. On the other hand, there are also more hydrophobic NADES, as illustrated in Figure 1. Marinaccio *et al*. (2024) investigated the extraction efficiency of menthol-thymol NADES (1:1 molar ratio) for recovering lycopene from tomato peel waste and compared its performance with conventional solvents such as α-pinene and n-hexane. The menthol-thymol mixture belongs to the type V deep eutectic solvents (DES) category, characterized by its non-ionic nature, low viscosity, chloride-free composition, and predominantly hydrophobic properties (Abranches *et al*., 2019; Osch *et al*., 2015; Osch *et al*., 2020; Busato *et al*., 2023).

NADES preparation involves mixing HBAs and HBDs through various methods, such as: 1) Heating (50–100°C) and stirring at 100 rpm for 30 minutes until a homogeneous, transparent liquid is formed (a simple and cost-effective method), 2) Freeze drying at 273 K (-20.15°C), 3) Evaporation at 50°C, 4) Grinding at room temperature (simple and cost-effective), 5) Ultrasonication, where a vortex homogenizes the mixture for one minute, followed by ultrasonic bath treatment for 30 minutes. This process is repeated with an additional ultrasonic treatment for 15 minutes, and 6) Microwave-assisted synthesis, involving vortex homogenization for one minute, followed by microwave treatment for 45 minutes at 80°C, 850 W, and 600 rpm (Fu *et al*., 2021).

The mechanism of extracting phenolic compounds using NADES combined with Ultrasonic-Assisted Extraction (UAE) is illustrated in Figure 2. During the extraction process, NADES penetrates and erodes the cell wall, exposing the intracellular structures. This exposure increases the generation of asymmetric collapse jets, facilitating greater penetration of NADES into the cell interior. Concurrently, intracellular components, including phenolic compounds, are released. Ultrasonic propagation mediated by NADES induces compression and rarefaction cycles, generating cavitation bubbles once the threshold is surpassed. The implosion and collapse of these bubbles alter the solvent properties, enhancing the efficiency of the extraction process (Habib and Ibrahim, 2009). Cavitation effects further damage the cell structure, allowing for the release of more intracellular components and improving the recovery of target compounds. Additionally, the low vapor pressure of NADES supports the formation of high-power cavitation, significantly boosting extraction efficiency (Cao *et al*., 2019).

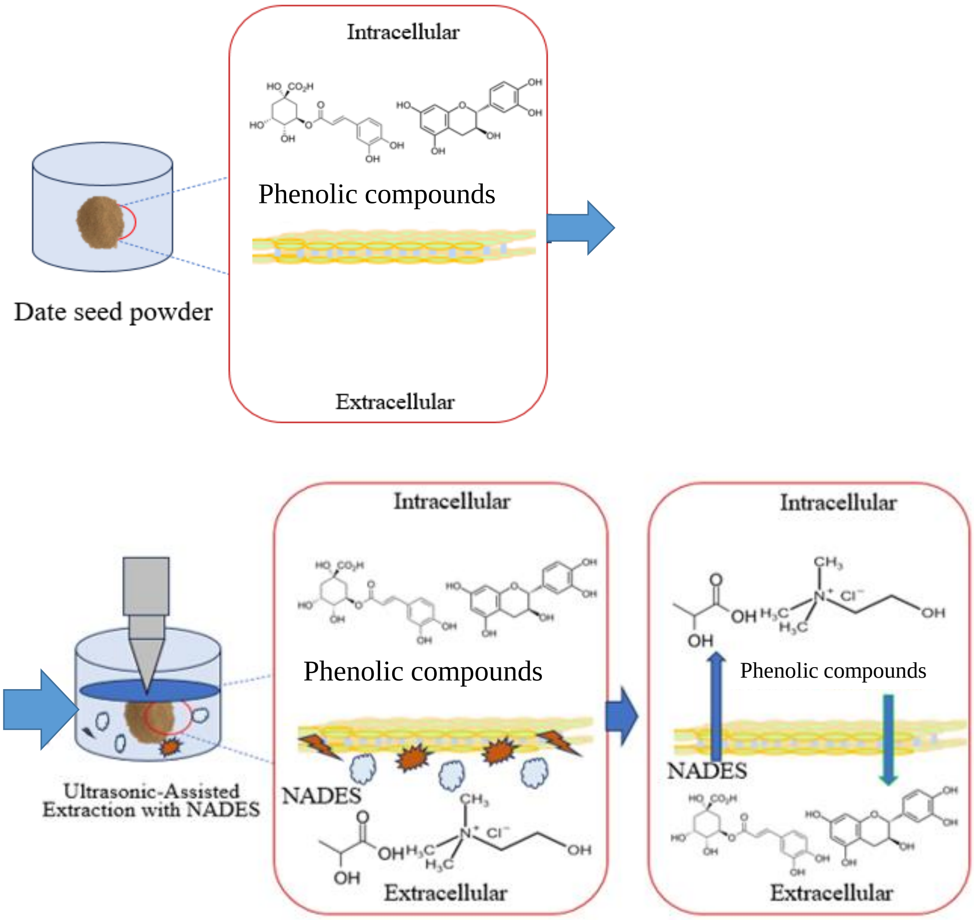

Figure 2. The mechanism of NADES in enhancing the extraction of phenolic compounds via ultrasonic-assisted extraction.

Comparison of yield and extraction efficiency between NADES and conventional methods

Enhanced yield with NADES, several studies have confirmed that NADES-based extraction techniques significantly improve the yield of bioactive compounds compared to conventional methods. For instance, polyphenol extraction using NADES composed of choline chloride (ChCl) and lactic acid (LA) with ultrasonic assistance resulted in a catechin content of 203.74 mg/100 g in Table 1, while conventional water-based extraction produced only 14.43 mg/100 g (Bijami *et al.*, 2020; Airouyuwa et al., 2023a). This demonstrates an increase of up to 14 times in catechin recovery. Meanwhile, chlorogenic acid, which was previously undetected by water extraction, became detectable by NADES assisted UAE at 307.38 mg/100 g in the same phase (tamr).

Table 1. Bioactive components (polyphenols) of date palm seeds extracted with green solvents during developmental stages (Bijami *et al*., 2020; Airouyuwa *et al*., 2023a).

Polyphenols (mg/100 g DW)	Hababouk 1 month	Kimri 2 months	Khalal 3 months	Tamr 4 months	Tamr 4 months
	Extract with water				Extract with Green Solvent NADES ChCl-LA
Gallic acid	11.02	nd	nd	nd	nd
Cinnamic acid	nd	nd	nd	26.84	*
Catechin	nd	32.56	18.4	14.43	203.74
Chlorogenic acid	0.53	nd	nd	nd	307.38
p-Coumaric Acid	nd	0.68	11.72	11.14	21.92
Vanillin	3.59	3.6	8.3	2.95	*
Epicatechin	*	*	*	18.8	*
Protocatechuic Acid	*	*	*	7.9	131.68
Caffeoylsikimate	*	*	*	28.3	*
Syringic acid	*	*	*	*	21.19
Quercetin	*	*	*	*	95.00

Notes nd = not detected, * = not observed

Superior extraction efficiency in Table 2 shows that NADES-based extractions also reduce processing time and solvent consumption. UAE combined with NADES extraction duration to just 50 minutes at 60°C, while conventional maceration required 24 hours at room temperature. Furthermore, NADES-assisted UAE increased polyphenol yields to 140 mg GAE/g compared to maceration with distilled water, which yielded only 22.80 mg GAE/g (Airouyuwa *et al*., 2022). These findings highlight NADES as a more efficient and sustainable extraction method.

The substantial increase in yield achieved through NADES-based extractions underscores the superiority of this method over conventional techniques for obtaining bioactive compounds from date seeds. NADES enhances compound recovery, minimizes solvent usage, reduces energy consumption, and shortens processing time. These advantages align with the principles of green chemistry and modern food technology trends, making NADES a promising alternative for sustainable bioactive compound extraction.

Safety and Sensory Analysis of NADES in Vitro and in Vivo

The safety and sensory characteristics of natural deep eutectic solvents (NADES) have been extensively studied in vitro and in vivo. The literature suggests that many NADES formulations exhibit low cytotoxicity, with variations dependent on their specific composition. Paiva *et al*. (2014) reported no cytotoxic effects from NADES components, and many formulations demonstrated an absence of antimicrobial activity. Similarly, Huang *et al*. (2017) found that NADES did not inhibit the growth of Gram-positive (S. *aureus*, *L. monocytogenes*) or Gram-negative bacteria (E. *coli*, *S. enteritidis*), suggesting their potential suitability for food and pharmaceutical applications.

Table 2. Comparison of yield between NADES and conventional methods.

No	Material	Extraction Technique	Extraction Type	Total phenolic (mg GAE/g)	Total flavonoid (mg QE/g)	Reference
1	Khalas date seed powder	80% Ethanol	Conventional	42	29	Airouyuwa *et al.*, 2022
		80% Methanol	Conventional	41	18	Airouyuwa *et al.*, 2022
2	Date seeds from the Al-Jazira	Maceration 24h (70% ethanol)	Conventional	76.86	21.19	Giovanny *et al.*, 2020
	Bogor date juice industry	Aqueous extract.	Conventional	22.80	3.08	Giovanny *et al.*, 2020
3	Date seed powder (tamr)	UAE with NADES (80% amplitude, 15 min, 35–40°C)	Non-conventional	125.26	-	Airouyuwa *et al.*, 2022
4	Defatted date seed powder	NADES (ChCl:FA) with MAE 50 s, 400 W	Non-conventional	128	-	Kehili *et al.*, 2022
5	Khalas date seed powder (tamr)	UAE with NADES (ChCl:LA), 50 min, 60°C	Non-conventional	140	85	Airouyuwa *et al.*, 2023a

Notes: Tamr = dry ripe/mature ripe, ChCL:FA = Choline Chloride : Formic Acid; ChCL:LA = Choline Chloride : Lactic Acid

However, the toxicity of NADES can vary significantly depending on their molecular composition. Rodrigues *et al*. (2020) observed that mono- and diterpenic-based NADES exhibited toxicity toward intestinal epithelial cells (Caco-2), although they also demonstrated anticancer properties by inhibiting colorectal cancer cell lines (HT-29). Furthermore, all terpenoid-based NADES displayed antimicrobial activity, particularly against S. aureus and E. coli. These findings highlight the dual nature of NADES, where specific formulations may pose toxicity concerns while others could offer therapeutic benefits.

The in vivo application of NADES in enhancing bioavailability has also been explored. Faggian *et al*. (2016) demonstrated the ability of NADES, composed of sugars, amino acids, and organic acids, to improve the solubility and pharmacokinetics of bioactive compounds. Specifically, rutin dissolved in a proline/glutamic acid (2:1) eutectic mixture exhibited enhanced plasma retention and bioavailability in Balb/c mice compared to an aqueous suspension. This suggests that NADES could be employed to optimize the delivery and efficacy of bioactive compounds in nutraceutical and pharmaceutical formulations.

In addition to their bioavailability-enhancing potential, NADES have been investigated for food fortification and extraction of functional compounds. Manuela et al. (2020) reported that polyphenol-rich extracts from cocoa by-products prepared using choline chloride-glucose and betaine-glucose NADES exhibited cytotoxic effects, reducing cancer cell viability by up to 40% at concentrations of 2–5% (v/v). While this demonstrates potential anticancer properties, it also raises concerns regarding their safe consumption at higher concentrations. The study also addressed the sensory evaluation of NADES-fortified chocolate milk using an electronic tongue system, avoiding legal and ethical challenges associated with human consumption trials. This approach allowed for an objective assessment of sensory characteristics, demonstrating the feasibility of NADES applications in functional food development.

Further work by Gomez-Urios *et al*. (2024) examined the incorporation of orange peel extract using NADES in orange juice, evaluating sensory profiles with electronic tongue (e-tongue) and electronic nose (e-nose) technologies. Their findings indicated that concentrations up to 15% did not significantly alter the sensory characteristics of the juice while providing a 160% increase in total polyphenol content compared to pure orange juice. These results suggest that NADES offer an environmentally friendly approach for extracting and formulating bioactive-enriched food products.

Despite promising applications, significant limitations remain regarding the regulatory approval and safety of NADES for human consumption. Many NADES components are considered safe (GRAS), but their novel combinations require further toxicological assessments. Additionally, while electronic sensory analysis provides valuable preliminary insights, human-based sensory evaluations are necessary for market acceptance. Moreover, the long-term effects of NADES consumption remain unexplored, necessitating further in vivo and clinical studies to ensure their safety and efficacy.

In future directions, using NADES in pharmaceuticals, nutraceuticals, and food applications presents exciting opportunities for enhancing the bioavailability, stability, and functional properties of bioactive compounds. However, before widespread adoption, several challenges must be addressed. Future research should focus on conducting comprehensive toxicological assessments to ensure the safety of various NADES formulations, particularly in long-term consumption studies. Additionally, regulatory frameworks must be established to guide the safe use of NADES in food and pharmaceuticals.

From an industry perspective, optimizing NADES formulations for large-scale production and cost-effectiveness will be critical. Efforts should be directed toward improving extraction efficiency, minimizing adverse sensory impacts, and ensuring NADES-based formulations meet consumer preferences. Further integration of human sensory trials, alongside electronic tongue and nose assessments, will be crucial for validating consumer acceptance.

By addressing these research gaps and industrial challenges, NADES have the potential to revolutionize bioactive compound delivery, offering sustainable, efficient, and health-promoting alternatives in multiple sectors.

Potential of date seeds extract using NADES as food ingredients

Takaeidi *et al*. (2014) demonstrated that date palm seeds are non-toxic, a finding supported by Mansour *et al*. (2011), who confirmed the safety of date seed oil. Furthermore, Al-farisi and Lee (2014) highlighted that date seed powder, commonly used in confectionery products such as cakes, sweet bread, and pastries, is a rich source of fiber and antioxidants. Its consumption improves antioxidant status and reduces oxidative damage in premenopausal women (Saryono *et al*., 2017).

Table 3 illustrates that NADES (Natural Deep Eutectic Solvents) extracts derived from date seeds are primarily utilized as functional food ingredients. These extracts contain polysaccharides, mono-oligosaccharides, antioxidants, phytosterols, carotenoids, and polyphenols. The potential applications of NADES-derived food ingredients are anticipated to expand in the future. Some notable applications include:

Polysaccharides, can enhance the functional properties of food products by serving as thickeners in sauces and soups. Additionally, they act as emulsion stabilizers in products such as salad dressings, ice cream, and mayonnaise. Date seed extracts function as natural stabilizers in nanoemulsion systems, enhancing stability, reducing droplet size, and improving antioxidant activity. Niroula *et al*. (2024) observed that nanoemulsions with date seed extract remained stable for seven days under refrigerated conditions, with droplets below 100 nm.

Mono-oligosaccharides, function as prebiotics and can be incorporated into yoghurt, serve as texture stabilizers in ice cream, sauces, and dairy products, act as air-binding agents in bread, and function as emulsifiers and stabilizers in various dairy products. Date seed powder (DSP) has been utilized as a prebiotic and natural stabilizer in yoghurt. DSP enriched the product with dietary fibre and resistant starch, improved sensory properties, and reduced syneresis (El-Kholy, 2018; Kehili *et al*., 2022).

Antioxidants, these act as natural preservatives in cooking oil, margarine, butter, biscuits, sausages, and nuggets. They also extend the shelf life of bakery products, ready-to-eat beverages, and frozen foods by inhibiting oxidative damage. Moreover, they are used for food fortification in milk, cereals, and energy drinks.

Phytosterols, these compounds are used as cholesterol-lowering agents in functional foods. They can be applied in low-cholesterol margarine, probiotic drinks, fermented milk, functional yoghurt, and breakfast cereals. Additionally, they enhance the stability of fats and oils and serve as active ingredients in cardiovascular health-supporting foods, such as fortified fruit juices and snack bars.

Table 3. Utilization of date seeds as food ingredients.

No.	Material	Application/ Utilization	Extraction Methods	Key Outcomes	References
1	Defatted date seed powder	Polysaccharide extract as a functional food ingredient	NADES Choline chloride: Ethylene glycol (1:1) with 10% water, followed by ultrasonic-assisted extraction (UAE)	Polysaccharides exhibited antimicrobial activity against *E. coli* O157:H7, *S. typhimurium*, *S. aureus*, and *L. monocytogenes*, indicating potential use in milk and yogurt.	Subhash *et al.*, 2024
2	Khalas date seed powder	Polyphenols for preserving *Oreochromis niloticus* fillets	Polyol-based DES (ChCl:Eg) with microwave-assisted extraction (MAE), homogenization-assisted extraction (HAE), and UAE	MAE extended the shelf life of tilapia fillets at 4°C for 10 days. Polyphenol extracts inhibited microbial growth, maintaining total bacterial count (TBC) < 6 log CFU/g.	Airouyuwa *et al.*, 2024
3	Defatted Deglet Nour date seed powder	Polyphenols, mono-oligosaccharides as functional food ingredients	Microwave-assisted deep eutectic solvents (MW-DES) with supercritical CO_2 under varying conditions	Optimal extraction conditions yielded 128 g GAE/kg polyphenols under DES conditions: solid/solvent ratio 1:20 (g/mL), extraction time 50 seconds, microwave power 400 W.	Kehili *et al.*, 2022
4	Date seed powder	Phytosterols as functional food ingredients	NADES Menthol:Eucalyptol (1:1), Octanoic acid:L-Proline (4:1), Hexane (control) solid to liquid ratio 3 g/ml for extraction phytosterols with Heating-Stirring methods at 25°C	Menthol:Eucalyptol yielded the highest phytosterol content (8.6 ± 0.9 mg/g) at 25°C, outperforming Octanoic acid:L-Proline (2.0 ± 0.4 mg/g) and Hexane (0.4 ± 0.0 mg/g).	Rosell *et al.*, 2024a
5	Date seed powder	Carotenoid as functional food ingredients	NADES hydrophobic octanoic acid:L-proline (2:0.5), octanoic acid:lauric acid (3:1) compared to Hexane (control)	The highest carotenoid yield was from Octanoic acid:L-Proline (4.1 mg/100 g), followed by Octanoic acid:Lauric acid (0.3 mg/100 g) and Hexane (0.05 mg/100 g).	Rosell *et al.*, 2024b

Carotenoids are natural colourants in coloured beverage products (e.g., fruit juices and energy drinks), bakery products (e.g., cakes and biscuits), ice creams, and frozen desserts. Carotenoids also offer health benefits for the eyes and skin, making them suitable for inclusion in functional products such as probiotic drinks and snack bars.

Polyphenols, are natural antioxidants applicable in cooking oil products, processed meats, and functional food fortification, such as probiotic yoghurt, energy drinks, and breakfast cereals. Polyphenols also contribute to functional beverages that increase antioxidant activity, such as fruit juices, herbal drinks, and functional teas. Furthermore, Airouyuwa *et al*. (2024) reported that Polyphenol-rich NADES extracts were effective in preserving *Oreochromis niloticus* fillets, extending shelf life at 4°C for up to 10 days while maintaining microbial quality below acceptable limits.

Discussion of Findings

This review highlights the superior potential of Natural Deep Eutectic Solvents (NADES) for extracting bioactive compounds from date seeds compared to conventional methods. Key findings reveal that NADES-based extraction significantly enhances the yield of phenolic compounds, such as catechins and chlorogenic acid, offering a 2 to 5.5-fold increase in total phenolic content compared to maceration. This aligns with the principles of green chemistry, emphasizing sustainability and efficiency.

Combining ultrasonic-assisted extraction (UAE) with NADES has demonstrated remarkable efficiency in cell wall disruption, cavitation effects, and solute stabilization. These mechanisms improve the recovery of thermolabile phytochemicals, suggesting a transformative approach to utilizing underexplored by-products like date seeds. Furthermore, the versatility of NADES in terms of hydrophilic and hydrophobic compositions expands their applicability to a wide range of bioactive compounds, as demonstrated by the extraction of carotenoids, phytosterols, polysaccharides, and polyphenols.

In functional food development, the extracted bioactive components exhibit substantial potential. Polyphenols derived using NADES preserve food products such as *Oreochromis niloticus* fillets and offer antioxidative benefits for various applications, including bakery products and ready-to-eat beverages. Similarly, carotenoids and phytosterols extracted with NADES are applicable as natural colourants and cholesterol-lowering agents, respectively.

Despite these advancements, challenges remain in scaling up NADES-based extraction processes and ensuring the economic feasibility of their industrial applications. Future studies should focus on optimizing the extraction parameters, validating sensory profiles, and assessing the long-term safety of NADES-derived food ingredients in human consumption.

By leveraging NADES for green extraction, this study bridges the gap between waste valorization and sustainable food innovation. These findings underline the transformative role of date seeds as valuable resources for functional food systems, aligning with the Sustainable Development Goals (SDGs) for promoting responsible consumption and production.

Conclusions

This review highlights the transformative potential of Natural Deep Eutectic Solvents (NADES) in the green extraction of bioactive compounds from *Phoenix dactylifera* L. (date seeds), an underutilized by-product with significant value in the functional food industry. While NADES offer advantages in extraction efficiency, environmental sustainability, and alignment with circular economy principles, several critical challenges remain. Future research should prioritize comprehensive toxicological assessments, particularly the long-term effects of NADES consumption, to ensure their safety in food applications. Additionally, establishing of regulatory frameworks is essential to guide the safe use of NADES in consumable products. From an industrial perspective, optimizing NADES formulations for large-scale production and cost-effectiveness is crucial. Efforts should improve extraction efficiency, minimize undesirable sensory impacts, and ensuring that NADES-based formulations align with consumer preferences. These findings underscore the innovative applications of date seeds and contribute to advancing of sustainable food systems and responsible resource utilization in line with global sustainability goals.

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